ELECTROMAGNETIC ENVIRONMENT PRODUCED BY A MOVING CONDUCTING BODY IN A MAGNETIZED COLLISIONLESS PLASMA

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Abstract

To explain self–consistently the energetic processes, radiation features, and electromagnetic environment near the Io satellite, moving in the Jovian magnetospheric plasma, as well as a spacecraft body, or a plasma probe, we consider by means of plasma kinetic theory the process of the electromagnetic interaction between a moving conducting body and the surrounding hot magnetized plasma, described by the tensor $\varepsilon_{ij}(\omega, \mathbf{k})$. The fields structure is studied in terms of the low–frequency non-propagating inductive electromagnetic mode which is usually ignored. The investigation of the plasma dielectric properties for the frequency ranges $k_{\|}V_i \ll \omega \ll k_{\|}V_e, \omega \ll \Omega_{i,e}$ and $\omega \ll k_{\|}V_i \ll k_{\|}V_e, \omega \ll \Omega_{i,e}$ is performed. Our analysis shows the importance of the inductive electromagnetic fields and the effects of plasma spatial dispersion, related to the particles thermal motion. These fields are localized in the vicinity of the moving conducting body and decay in space due to a collisionless energy dissipation. They form a kind of a local magnetosphere of the conductor. Along with the influence of the energy losses of the moving conducting body, the inductive fields could also be responsible for the appearance of electromagnetic structures near the body, where charged particles could be effectively accelerated. The developed general analysis is applicable also for the cases of any artificial spacecraft body, or tethered satellite system slowly ($V_0 \ll V_A,\ V_e$) moving in the magnetized plasma of the ionosphere and in a low earth orbit.

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1 Introduction

We discuss here some aspects of interaction between a moving conducting body and a magnetized plasma. This is a topic with many applications. Among them there are for example problems arising around Io–Jovian magnetospheric interaction as well as some questions dealt with a spacecraft or tethered satellite systems moving in the ionosphere and in low earth orbit. In its general formulation the problem of interaction between conducting body and magnetized plasma in relative motion is rather old, and have already been considered in many works from different points of view, using various approaches [Drell et al., 1965; Gurevich et al., 1978; Barnett and Olbert, 1986; McKenzie, 1991].

The basic feature of the situation which we meet here is the presence of magnetic field which not only causes spatial anisotropy of plasma dielectric properties, but also is responsible for the electric field $1/c[\mathbf{V} \times \mathbf{B}]$ occurrence in the reference frame, connected with a moving conducting body. This electric field in its turn produces a current in or on the body, which generates significant perturbations in the surrounding plasma. The structure of these perturbations was usually studied using cold plasma MHD model.

Already in the first work [Drell et al., 1965] there was shown that large conducting object moving in magnetized plasma will radiate Alfvén waves, which will form so called "Alfvén wings". The existence such Alfvén wings was for example confirmed by in situ observations of magnetic field and plasma perturbations generated by Io in the Jovian magnetosphere.

Our particular interest to this rather general problem of interaction between moving conducting body and magnetized plasma have grown from the tasks of explanation of some features of the Jovian decametric radio emission which are usually associated with the effects arising due to the strong electromagnetic interaction between the moving Io satellite and Jovian magnetosphere. These effects could result in heating and acceleration of charged particles, which in their turn influence the Jovian radio emission.

Usually for the explanation of fast particles generation, the current system of Alfvén wings connected with Io is considered. In such models particles are assumed to be accelerated due to the presence of a considerable decrease of a potential along each of the force lines, caused by a break of current circuit in the Io magnetic tube, or by the effects appearing in the front region of the Alfvén shock wave [Shaposhnikov and Zaitsev, 1993]. At the same time the real structure of electromagnetic field and current system, excited by Io moving in the surrounding Jovian magnetospheric plasma is more complicated than just a conglomerate of Alfvén and magnetoacoustic wings. This concerns especially the regions in the vicinity of the satellite. Plasma parameters of the Io torus ($T \sim 10^4 \div 10^5$ K, $n \sim 2 \cdot 10^3$ cm^{-3}, $B \sim 2 \cdot 10^{-2}$ G) give us a reason to speak that on the scales up to a few tens of Io radii the effects of plasma particles collisions are not important, and plasma MHD approximation is inapplicable for the analysis of electromagnetic fields and currents structure in these near the satellite regions. The effects of plasma spatial dispersion, connected with particle thermal motion, together with the anisotropy of plasma dielectric properties, caused by the background magnetic field, lead to slurring over the wing–like field structure near moving conducting body, producing a specific electromagnetic environment [Gubchenko, 1989; Khodachenko and Gubchenko, 1997; Khodachenko et al., 1998], which appears in fact to be a major object for our investigation. It is natural to expect the appearance of certain bow and tail electromagnetic structures localized near the satellite and comoving it. These structures are formed mainly by the non-propagating decaying in space quasistationary inductive electromagnetic fields and could be considered as some kind of a local magnetosphere of a moving conductor. Except the general theoretical interest, these bow and tail electromagnetic structures are important as a factor, influencing energy losses of the moving conducting body, as well as an alternative source of fast particles which could be effectively generated in probably existing X–type magnetic configurations.

In order to describe adequately a fine structure of fields in the vicinity of moving in the magnetized plasma conducting body, with the effects of plasma spatial dispersion taken into account, plasma kinetic approach should be applied for the treatment of the named problem in stead of traditional MHD one.

2 General specifics of the problem

It is well known that plasma properties strongly depend on the presence of external electromagnetic fields, causing the anisotropy of medium, and on the frequency band. Even in the simple case of isotropic plasma when the dielectric permittivity tensor is a diagonal one, and vortical ($\mathbf{E}(\mathbf{k},\omega) \perp \mathbf{k}$) and potential ($\mathbf{E}(\mathbf{k},\omega) \parallel \mathbf{k}$) fields are excited independently, there exist many eigen–modes with respect to which, depending on the frequency, plasma sometimes behaves as a dielectric, and sometimes as a conducting medium. The anisotropy of magnetized plasma causes more complicated structure of the dielectric permittivity tensor. This in its turn causes a complicated connection between potential, and vortical fields. Plasma properties depend already not only on a frequency, but also on a direction of wave propagation. Magnetized plasma properties are well studied in the limiting cases. Among them there are first of all the cases of cold magnetized plasma. At the same time, of traditional interest were sufficiently high frequency fields of radiation, in the regions far from the source. This caused the situation when the specifics of generation of the low–frequency electromagnetic fields in the regions near the radiating source, for which the effects of plasma particles thermal motion become to be important, till now remains to be unclear. These fields were also out of the scope of interest of experimentalists, since their generation requires creation of large volumes of hot rarefied collisionless plasma (technically difficult task). In fact the low frequency inductive electromagnetic fields appear as a specific natural cosmic phenomenon which requires its special study.

We perform our analysis using well known traditional Fourier transform technique with direct and inverse Fourier transforms

$$\tilde{\mathbf{F}}(\mathbf{k},\omega) = \frac{1}{(2\pi)3}\int dt \int d^3k e^{i\omega t - i\mathbf{kr}}\mathbf{F}(\mathbf{r},t), \tag{1}$$

$$\mathbf{F}(\mathbf{r},t) = \int \frac{d\omega}{2\pi}\int d^3k e^{-i\omega t + i\mathbf{kr}}\tilde{\mathbf{F}}(\mathbf{k},\omega). \tag{2}$$

There are two frames of reference which are natural for our problem: The rest frame of the ambient plasma, which denote K and the rest frame of the conductor K'. For non-relativistic motion the respective space-time coordinates $(\mathbf{r}, t)$ and $(\mathbf{r}', t')$ are related each other as $\mathbf{r}' = \mathbf{r} - \mathbf{V}_0 t,$ and$t' = t$ where $\mathbf{V}_0$ is velocity of the body.

If we'll rewrite the expression (2) in the frame of reference attached to the moving body, we'll obtain

$$\mathbf{F}(\mathbf{r}', t) = \int \frac{d\omega}{2\pi} \int d^3k e^{-i(\omega - \mathbf{kV}_0)t + i\mathbf{kr}'} \tilde{\mathbf{F}}(\mathbf{k}, \omega). \tag{3}$$

Since we are interested in fields which do not depend on time when viewed from the comoving frame of reference, then the equality $\mathbf{F}(\mathbf{r}', t) = \mathbf{F}(\mathbf{r}')$ should take place. There exist just one way to remove time dependence from the equation (3). It is to consider the Fourier image of the field to be $\tilde{\mathbf{F}}(\mathbf{k}, \omega) = 2\pi\delta(\omega - \mathbf{kV}_0)\tilde{\mathbf{F}}'(\mathbf{k})$. In this case the integration over ω yields from relation (3)

$$\mathbf{F}(\mathbf{r}') = \int d^3k e^{i\mathbf{kr}'} \tilde{\mathbf{F}}'(\mathbf{k}).$$

Here $\tilde{\mathbf{F}}'(\mathbf{k})$ is a Fourier image of a field $\mathbf{F}(\mathbf{r}')$ which is steady-state in the reference frame attached to the moving body. Therefore, the integration over the ω in our further analysis looks as a simple replacement of the ω onto the $\mathbf{kV}_0$. So, to make any general predictions concerning the structure and behavior of electromagnetic fields generated in the vicinity of a moving conducting body in a magnetized plasma we should study the dielectric properties of plasma on the frequencies [Khodachenko et al., 1998]

$$\omega = \mathbf{kV}_0. \tag{4}$$

3 Some important plasma dielectric properties

Io–related application of the general problem of a conducting body moving in a magnetized plasma supposes that we consider here the case of a slow motion of the body with respect to Alfvén V_A and thermal electron V_e velocities, whereas thermal ion velocity V_i remains to be less then one of the conductor ($V_i \ll V_0 \ll V_e$). Besides, we are interested in the fields with the wave length greater then a gyroradius of particles ($kV_\alpha \ll \mid \Omega_\alpha \mid = (q_\alpha B)/(m_\alpha c), \alpha = e, i$). All this means that the frequency range of interest in our particular Io-related case is the low frequency range $k_\| V_i \ll \omega \ll k_\| V_e$, $\omega \ll \Omega_{i,e}$.

The components of tensor of dielectric permittivity of magnetized plasma in this low frequency band are as follows

$$\varepsilon_{xx} = \frac{\omega_i^2}{\Omega_i^2} = \frac{c^2}{V_A^2}, \quad \varepsilon_{yy} = \varepsilon_{xx} + i\sqrt{2\pi}\frac{\omega_e^2}{\Omega_e^2}\frac{k_\perp^2 V_e}{\mid k_\| \mid \omega},$$

$$\varepsilon_{zz} = 1 - \frac{k_\perp^2}{k_\|^2}\frac{\omega_e^2}{\Omega_e^2} - \frac{\omega_i^2}{\omega 2} + \frac{\omega_e^2}{k_\|^2 V_e^2}\left(1 + i\sqrt{\frac{\pi}{2}}\frac{\omega}{\mid k_\| \mid V_e}\right), \tag{5}$$

$$\varepsilon_{yz} = -\varepsilon_{zy} = i\frac{\omega_e^2}{\omega\Omega_e}\frac{k_\perp}{\mid k_\| \mid}\left(1 + i\sqrt{\frac{\pi}{2}}\frac{\omega}{\mid k_\| \mid V_e}\right), \quad \varepsilon_{xy} = \varepsilon_{yx} = \varepsilon_{xz} = \varepsilon_{zx} = 0.$$

Magnetized plasma anisotropy causes the appearance of the nondiagonal components of the dielectric tensor, whereas the effects of spatial dispersion due to particles thermal motion lead to the existence of the imaginary terms. This, in particular, means that a collisionless dissipation of the energy of electromagnetic fields due to their interaction with the resonant thermal particles takes place.

Dispersion equation of plasma modes in this case looks like

$$\det(\hat{\Lambda}) = \det\left(k^2\delta_{ij} - k_ik_j - \frac{\omega^2}{c^2}\varepsilon_{ij}(\mathbf{k},\omega)\right) = \lambda_{xx}(\lambda_{yy}\lambda_{zz} + \lambda_{yz}^2) - (k_\perp k_\parallel)^2\lambda_{yy} = 0. \quad (6)$$

where

$$\lambda_{xx} = k_\parallel^2 - \frac{\omega^2}{c^2}\varepsilon_{xx}, \quad \lambda_{yy} = k^2 - \frac{\omega^2}{c^2}\varepsilon_{yy}, \quad \lambda_{zz} = k_\perp^2 - \frac{\omega 2}{c2}\varepsilon_{zz}, \quad \lambda_{yz} = -\lambda_{zy} = -\frac{\omega^2}{c^2}\varepsilon_{yz}.$$

For the modes propagating along the background magnetic field ($k_\perp = 0$) the dispersion equation (6) has more simple form, $\det(\hat{\Lambda}) = \lambda_{xx}^2\lambda_{zz} = 0$, according to which a slowly moving conducting body generates linearly polarized Alfvén wave propagating along the background magnetic field

$$\lambda_{xx} = 0 \quad \Longrightarrow \quad \omega^2 = k_\parallel^2 V_A^2,$$

and, decaying due to interaction with a resonant thermal electrons, ion low frequency plasma wave

$$\lambda_{zz} = 0 \quad \Longrightarrow \quad \frac{\omega_i^2}{c2} - \frac{\omega^2}{c^2}\frac{\omega_e^2}{k_\parallel^2 V_e^2}\left(1 + i\sqrt{\frac{\pi}{2}}\frac{\omega}{\mid k_\parallel \mid V_e}\right) = 0.$$

There exist also fast (+) and slow (−) magnetoacoustic waves whose spectra in the case of the low pressure plasma, i.e., $\beta = V_s^2/V_A^2 \ll 1$ (Jovian case) look like

$$\omega_+^2 = k^2 V_A^2, \quad \delta_+ = -\sqrt{\frac{\pi m_e}{8m_i}}\frac{V_s}{V_A}\frac{\sin^2\theta}{\mid\cos\theta\mid}\omega_+,$$

$$\omega_-^2 = k^2 V_s^2\cos^2\theta, \quad \delta_- = -\sqrt{\frac{\pi m_e}{8m_i}}\omega_-.$$

Here $\delta_\pm$ are the decrements characterizing wave decay in time ($\omega_\pm^* = \omega_\pm + i\delta_\pm$); $V_s = \sqrt{k_B T_e/M_i}$, ion sound velocity; θ, the angle between magnetic field and direction of wave propagation. Note, that fast magnetoacoustic wave appears in fact as a continuation of fast MHD wave into the region of small phase velocities ($\omega/k_\parallel \ll V_e$). In this very case fast magnetoacoustic wave is purely transverse ($\mathbf{E} \perp \mathbf{k}$), whereas slow magnetoacoustic wave in the low pressure plasma degenerates into purely longitudinal (potential) one ($\mathbf{E} \parallel \mathbf{k}$).

To study the behavior of the low frequency fields, propagating in the arbitrary direction with respect to the background magnetic field ($k_\parallel \neq 0$, $k_\perp \neq 0$) we pay our attention to the fact that the component ε_{yy} of the plasma dielectric permittivity tensor can be represented as $\varepsilon_{yy} = \varepsilon_{xx} + iIm(\varepsilon_{yy})$. This in its turn allows us to represent λ_{yy} as $\lambda_{yy} = \lambda_{xx} + k_\perp^2 - \frac{\omega 2}{c2}iIm(\varepsilon_{yy})$. Taking these relations into account the dispersion equation (6) can be rewritten in the following form

$$\lambda_{xx}\left[\left(k_\perp^2 - \frac{\omega^2}{c^2}iIm(\varepsilon_{yy}) + \lambda_{xx}\right)\lambda_{zz} + \lambda_{yz}^2\right] - (k_\perp k_\parallel)^2\left(k_\perp^2 - \frac{\omega^2}{c^2}iIm(\varepsilon_{yy}) + \lambda_{xx}\right) = 0. \quad (7)$$

From (7) follows the existence of a particular solution characterized by the set of equations:

$$\begin{cases} k_\perp^2 - \frac{\omega^2}{c^2} iIm(\varepsilon_{yy}) = 0, \\ \\ \lambda_{xx}\lambda_{zz} + \lambda_{yz}^2 - (k_\perp k_\parallel)^2 = 0. \end{cases}$$

The first equation of the set in the case $k_\perp \neq 0$ gives the relation between $k_\parallel$ and ω

$$\mid k_\parallel \mid = i\frac{\omega}{c^2}\sqrt{2\pi}\frac{\omega_e^2 V_e}{\Omega_e}. \quad (8)$$

whereas the second equation together with (8) taken into account gives the relation between $k_\perp$ and ω, which for the Jovian magnetospheric plasma parameters near the Io satellite looks like

$$k_\perp^2 \approx \omega^2 \frac{2\pi\omega_e^2 V_e^2}{c^4\Omega_e^2} \frac{\left(\omega^2 - \frac{c^6\Omega_e^6}{4\pi\omega_e^4 V_e^6}\right)}{\left(\omega^2 + \frac{V_A^2 c^2 \Omega_e^4}{4V_e^4\omega_e^2}\right)}.$$

The fact that for this very mode the longitudinal with respect to the background magnetic field component of vector k is imaginary means that the fields propagating not exactly parallel to the external magnetic field decay along the background magnetic field and form some kind of stretched structure on the line of motion of the body.

It is important to note here that when one considers the interaction between a moving conducting body and a magnetized plasma one more characteristic direction of the problem appears besides of the direction of external magnetic field $\mathbf{B}_0$. It is the direction of the velocity $\mathbf{V}_0$ of the body. Plasma properties appear to be in a strong dependence also on the direction of wave propagation with respect to $\mathbf{V}_0$. This means that the characteristic frequency of co-moving electromagnetic fields $\omega = \mathbf{kV}_0 = \mathbf{k}_\perp\mathbf{V}_0$ changes in dependence of value of $\mathbf{k}_\perp$. In particular, for the simple 2–dimensional case of an infinite conducting cylinder moving across the magnetic field $(\mathbf{B}(0,0,B_0);\ \mathbf{V}_0(V_0,0,0),\ \ \mathbf{k}(k_x,0k_z))$ the asymptotical expressions (5) for the components of plasma dielectric permittivity tensor remain to be valid for

$$\begin{cases} \frac{|k_z|}{|k_x|} \gg \frac{V_0}{V_e} \ll 1, \\ \\ \frac{|k_z|}{|k_x|} \ll \frac{V_0}{V_i} \gg 1. \end{cases}$$

which correspond to the situation $k_z V_i \ll \omega = V_0 k_x \ll k_z V_e,\ \omega = V_0 k_x \ll \Omega_{i,e}$. At the same time, for the case $k_x \to 0$ we appear in the very low frequency situation: $\omega = V_0 k_x \ll k_z V_i \ll k_z V_e,\ \omega = V_0 k_x \ll \Omega_{i,e}$, where the fields decay not only due to interaction with resonant thermal electrons, but also due to interaction with thermal ions. Analogous, when $k_z \to 0$ we have $k_z V_i \ll k_z V_e \ll \omega = V_0 k_x,\ \omega = V_0 k_x \ll \Omega_{i,e}$, and the effects of particle thermal motion appear to be unimportant for such waves.

4 Conclusion

Here we limit ourselves first of all by the discussion of some features of the application of the general problem of interaction between a moving conducting body and a magnetized plasma for the tasks of Io-Jovian magnetospheric interaction in order to develop the methods of interpretation of some Jovian observational data, in particular, of some features of the Jovian decametric radio emission. The tasks of description of process of Io–Jovian magnetospheric interaction oblige us to consider the model with a slowly moving conducting body, with the effects of plasma particles thermal motion taken into account ($V_i \ll V_0 \ll V_e$). In this very case the low-frequency inductive electromagnetic fields are effectively generated in the vicinity of the conductor. To emphasize the importance of these low-frequency inductive electromagnetic fields, which form some kind of a local magnetosphere around the moving conductor, and influence its energetics and radiative features, was the main goal of the present paper. Another our goal which we tried to follow here was to perform a general analysis of plasma dielectric properties in the frequency bands corresponding to the co-moving electromagnetic fields, generated in vicinity of moving Io satellite in the Jovian magnetosphere, in order to predict some structural features of these fields.

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